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Research Article

Experimental Investigation of Effect of Process Parameters on Material Removal Rate during WEDM

Sumit Kumar[†*], S.K Garg[‡] and Gagandeep Chawla[†]

[†]Department of Mechanical Engineering, [‡]Seth Jai Parkas Mukund Lal Institute of Engineering & Technology, Radaur, Yamuna Nagar, Haryana, India

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Abstract

For any machining process and, particularly, in process related to Wire Electrical Discharge Machining (WEDM) the right selection of machining conditions is one of the most important aspects to be taken into consideration. WEDM is capable of machining of geometrically complex shapes or material components having higher hardness, that are precise and very difficult-to-machine such as composites, super alloys heat treated tool steels, ceramics, heat resistant steels, carbides etc. These hard material components are widely used in aerospace industries, die and mold making industries, aeronautics and nuclear industries. This investigation discusses the effects of machining parameters like pulse on time, pulse off time and voltage on the material removal rate of wire electric discharge machining. For this investigation, stainless steel (SS 304) has been used as a work piece and a brass wire and a diffused wire having 0.25 mm diameter is used as tool electrodes. The design of experiment is based on Taguchi Design approach L_9 orthogonal array. Further, the analysis of variance (ANOVA) is used to analyze the results obtained from Taguchi design approach. The analysis of results indicates that diffused wire gives more material removal rate (MRR) as compare to the brass wire. The results show that, the pulse on time and servo voltage has the highest influence on material removal rate (MRR). As the pulse on time increases, the material removal rate increases. It is also concludes that, with the increase of pulse off time and servo voltage, the material removal rate decreases.

Keywords: *Wire-Cut EDM; ANOVA; Material Removal Rate.*

1. Introduction

Wire-Cut EDM is a unique adoption of the non-conventional machining process, which uses an electrode to initialize the sparking process. Wire-Cut EDM utilizes a continuously travelling thin wire electrode made up of copper, brass or tungsten of diameter varies from 0.05 to 0.30 mm, which is capable of achieving very small corner radii. The thin wire electrode is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. During the Wire-Cut EDM process, the material is eroded ahead of the wire and there is no direct contact between the work piece and the wire, eliminating the mechanical stresses during machining. Wire-Cut EDM is used primarily for cut shapes through a selected part or assembly. With a Wire-Cut EDM machine, if a cutout needs to be created, an initial hole must first be drilled in the material, and then the wire can be fed through the hole to complete the machining. In a Wire-Cut EDM, the wire electrode is held vertically by two wire guides located separately above and below the work piece with the wire traveling longitudinally during machining. The work piece is usually mounted on an x-y table.

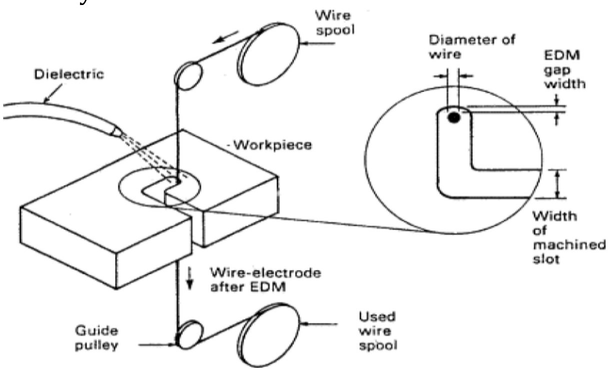

Fig. 1 Setup of Wire-Cut EDM

The Wire-Cut EDM machine tool comprises of a main worktable (X-Y) on which the work piece is clamped; an auxiliary table (U-V) and wire drive mechanism. The main table moves along X and Y-axis and it is driven by the D.C servo motors. The travelling wire is continuously fed from wire feed spool and collected on take up spool which moves though the work piece and

*Corresponding author **Sumit Kumar** is PG Scholar; **Dr. S.K Garg** is working as Director and **Gagandeep Chawla** as Assistant Professor is supported under tension between a pair of wire guides located at the opposite sides of the work piece. The lower wire guide is stationary whereas the upper wire guide, supported by the U-V table, can be displaced transversely along U and V-axis with respect to lower wire guide. The upper wire guide can also be positioned vertically along Z-axis by moving the quill. A series of electrical pulses generated by the pulse generator unit is applied between the work piece and the travelling wire electrode, to cause the electro erosion of the work piece material. As the process proceeds, the X-Y controller displaces the worktable carrying the work piece transversely along a predetermined path programmed in the controller. While the machining operation is continuous, the machining zone is continuously flushed with water passing through the nozzle on both sides of work piece. Since water is used as a dielectric medium, it is very important that water does not ionize. Therefore, in order to prevent the ionization of water, an ion exchange resin is used in the dielectric distribution system to maintain the conductivity of water.

2. Literature Review

Cyriac *et. al.* (2015), optimized the Wire-Cut EDM parameters of EN 24 steel by using Taguchi method. The process parameters selected for this experiment were pulse on time, pulse off time, current and speed. In this experiment the effect of above mentioned process parameters was observed on surface roughness. The design of experiment was based on Taguchi L_{16} orthogonal array. Analysis of variance (ANOVA) was used by the authors to find out the most significant parameter that affects the surface roughness. Further, the regression analysis was carried out to generate a mathematical model of surface roughness. From results, authors observed that current has major influence on surface roughness followed by pulse on time, pulse off time and cutting speed.

Singh *et. al.* (2015), investigated the Wire-Cut EDM to optimize the dimensional deviation of EN8 steel by using Taguchi design approach. Wire feed, servo voltage and pulse off time were the input parameters selected for this experiment. Dimensional deviation was the output parameter. Taguchi method was used to optimize the parameters and L_{18} orthogonal array was used for the statistical analysis. Authors observed that, among the three parameters servo voltage has the greatest effect on dimensional deviation and was followed by pulse off time and wire feed. Authors observed that, as the servo voltage and wire feed rate increases the dimensional deviation was decreases. And when the pulse off time increases, the dimensional deviation initially increases and further it decreases.

Sivaraman *et. al.* (2015), studied the effect of control parameters on material removal rate and surface finish during wire electric discharge machining. Titanium was used as a work piece material for this experiment. Pulse on time, pulse off time, wire feed rate, wire tension, gap voltage, dielectric pressure and table feed were the control parameters and material removal rate and surface finish were the performance parameters. The design of experiment was based on Taguchi L_{18} orthogonal array. Further, analysis of variance (ANOVA) was used to find out the significance of each input parameter on the performance parameters i.e. material removal rate and surface finish. Authors observed that, pulse off time was the major influencing factor for MRR followed by pulse on time, wire feed, gap voltage, wire tension, table feed and dielectric pressure. Authors also concluded that, gap voltage was the most influencing factor for surface roughness followed by pulse on time, pulse off time, wire feed rate, dielectric pressure, wire tension and gap voltage.

Nagaraja *et. al.* (2015), optimized the control parameters for metal matrix composite in Wire-Cut EDM. The bronze alumina (Al_2O_3) metal matrix composite was used as a work piece material. The cutting parameters considered in this experimental study were pulse on time, pulse off time and wire feed rate. Material removal rate and surface roughness were the performance parameters for this study. The experimental layout was based on Taguchi L_9 orthogonal array. Further, the analysis of variance (ANOVA) was used to analyze the effect of each cutting parameter on surface roughness and material removal rate. Authors concluded that; wire feed rate was the most significant parameter for surface roughness. As the pulse on time increases the surface roughness also increases.

Ramesh *et. al.* (2014), observed the impact of input parameters on material removal rate and surface roughness in wire electric discharge machining. The experiments were conducted on $Al6061/SiC_P/B_4C_P$ with molybdenum tool. De-ionized water was used as dielectric fluid. The results indicated that, increase in silicon carbide and boron carbide leads to decrease in both material removal rate and surface roughness. Authors observed that peak current (Ip) and pulse duration (Ton), have significant effect on the MRR and SR whereas the pulse off time does not have much effect.

Saini *et. al.* (2014), studied the effect of process variables on cutting velocity during wire electric discharge machining of Al/ZrO_2 metal matrix composite. Experiments were carried out using one factor at a time approach. Pulse width, time between pulses, servo control mean reference voltage, short pulse time and wire mechanical tension were the control parameters selected. Authors observed that the cutting velocity increases with the increase of pulse width and short pulse time and decreases with the increase of time between pulses and servo control mean reference voltage. However, cutting velocity remains constant with the increase of wire tension.

Saini *et. al.* (2014), determined the effect of control factors of wire electric discharge machining on material removal rate. Pulse width, maximum feed rate, dielectric conductivity, time between pulses, wire tension, injection pressure, short pulse time and servo control mean reference voltage were the process parameters selected for the experiment. The experiments were conducted on Ti-6Al-4V alloy. The design of experiment was based on Taguchi's L_{36} orthogonal array. From results authors observed that, as the short pulse time and pulse width increased, the MRR also increased. Further, with the decreased in servo control mean reference voltage, the MRR increased. Authors observed that the MRR decreases with the increase of wire feed rate and wire mechanical tension. The dielectric conductivity, maximum feed rate and injection pressure have no such effect on MRR.

Mathew *et. al.* (2014), found out the optimal process parameter setting of Wire-Cut EDM on SS 304. The material removal rate, surface roughness and dimensional deviation were the performance parameters for the optimization of pulse on time, pulse off time, servo voltage, wire feed, wire tension and dielectric pressure. The layout of experiment was based on Taguchi's L_{27} orthogonal array. Analysis of variance (ANOVA) was used to determine the optimum machining parameters for material removal rate, surface roughness and dimensional deviation. Authors concluded that all the parameters except wire feed and wire tension, significantly affects the material removal rate, surface roughness and dimensional deviation. The results showed that as the pulse on time increased, the MRR and SR also increased.

Lodhi *et. al.* (2014), optimized the machining parameters in Wire-Cut EDM of AISI D3 steel for surface roughness. The control parameters for the experiment were pulse on time, pulse off time, peak current and wire feed. The layout of design was based on Taguchi's L_9 orthogonal array. Analysis of variance (ANOVA) was used to find out most significant parameter for surface roughness. From results authors observed that the surface roughness was influenced by pulse on time followed by peak current and pulse off time.

Hemalatha *et .al.* (2014), analyzed the surface integrity in Wire-Cut EDM of Al 6063/ Al 203 metal matrix composites. Stir casting process was adopted for casting the composite plates with varying mass percentage of alumina (3%, 6% and 9%). Response surface methodology was used to design the layout of experiment. The pulse on time, pulse off time and servo feed were selected as machining parameters. From results, authors observed that with respect to decrease in pulse on time and weight percentage of alumina the kerf width decreased. And, with increase in pulse on time and weight percentage of alumina the surface roughness decreased.

Garg *et. al.* (2013), presented an experimental investigation of machining characteristics and the effect of wire-cut EDM process parameters during machining of Al/ZrO_2 particulate reinforced metal matrix composite (PRMMC) material. Central composite design (CCD) of response surface methodology (RSM) considering full factorial approach was used to design the experiment. Experiments were carried out to optimize the process parameters such as pulse width, time between pulses, servo control mean reference voltage, wire feed rate, wire tension and short pulse time for performance measures such as cutting velocity and surface roughness. The comparison of performance characteristics using different wire electrodes was also presented in this study. Authors concluded that, cutting velocity increases with the increase in pulse width and short pulse time. It also increases with increases in time between pulses and servo control mean reference voltage initially but then decreases further with the increase in time between pulses and servo control mean reference voltage. Wire feed rate was no such significant effect on cutting velocity. Authors observed that, surface roughness increases with the increases in pulse width and servo control mean reference voltage. Surface roughness also increases with the increase in time between pulses initially but decreases with the further increase in time between pulses. Authors also observed that, diffused wire electrode provides better results in its performance related to the cutting velocity, surface roughness and breakage as compared to the brass wire electrode.

3. Material and Methodology

3.1 Work Piece Material

The Wire Electric Discharge Machining is used to machine hard materials like steel, carbides and composites. The work piece material should be electrically conductive for an Electrical discharge machining process. Stainless Steel (SS 304) is used as a work piece material in this experiment. The chemical composition of stainless steel (SS304) is shown in table 1.

Table 1 Chemical Composition of SS 304

Elements	Wt %
Cr	18.1
Ni	8.02
Mn	1.211
Si	0.3677
C	0.0458
P	0.01349
S	0.00898

3.2 Process Parameters and Design of Experiment

The experimental layout for the machining parameters is based on the Taguchi design approach L_9 orthogonal array. This array consists of three control parameters viz. pulse on time, pulse off time and voltage and their three levels. In Taguchi method, mostly all of the observed values are calculated based on 'higher the better' and 'smaller the better'. Thus in this experiment, the observed values of MRR is set to maximum. In Taguchi method, S/N ratio is the measure of quality characteristics. S/N ratio is determined for material removal rate larger the better criterion by using equation (1). Next, the optimizations of the observed values are determined by analysis of variance (ANOVA) which is based on the Taguchi design approach.

$$SN_i = -10log \frac{1}{N_i} \sum_{u=1}^{N_i} \frac{1}{y^2} \quad (1)$$

Table 2 Process Parameters and their Levels

Process Parameters		Pulse on Time	Pulse off Time	Servo Voltage
Symbol		Ton	Toff	SV
Unit		µs	µs	Volt
Range	Min	100	0	0
	Max	131	63	99
Levels	Level 1	115	45	15
	Level 2	120	50	25
	Level 3	125	55	35

Table 3 L_9 Orthogonal Array in Terms of Actual Parameters

Column	C1	C2	C3	Response Data (MRR)	S/N Ratio
Run	Ton	Toff	SV		
1	115	45	15	-	-
2	115	50	25	-	-
3	115	55	35	-	-
4	120	45	25	-	-
5	120	50	35	-	-
6	120	55	15	-	-
7	125	45	35	-	-
8	125	50	15	-	-
9	125	55	25	-	-

4. Conduct of Experiment

Experimentally, a brass wire and a diffused wire are used as electrode. Stainless steel (SS 304) is used as a work piece material. The experiment is performed on Sprintcut Electronica Wire-Cut EDM machine. De-ionized water is used as a dielectric fluid with external pressure flushing. The process parameters used for experiment are pulse on time (Ton), pulse off time (Toff) and servo voltage (SV). The machining performance is evaluated in term of material removal rate (MRR). In this experiment peak current, flushing pressure, wire feed and wire tension are kept constant 230 Amp, 0.2kgf/cm^2, 8 m/min and 9 units respectively. The layout of design of experiment is based on Taguchi L_9 orthogonal array.

Table 4 Observation Table

Run	Pulse on Time (µs)	Pulse off Time (µs)	Servo Voltage (V)	MRR (mm^3/min)		S/N Ratio	
				Using Brass wire	Using Diffused Wire	Using Brass wire	Using Diffused Wire
1	115	45	15	7.63	7.85	17.650	17.897
2	115	50	25	5.75	5.96	15.193	15.505
3	115	55	35	4.37	4.57	12.809	13.198
4	120	45	25	9.47	9.61	19.527	19.655
5	120	50	35	7.39	7.60	17.373	17.616
6	120	55	15	8.35	8.56	18.434	18.649
7	125	45	35	10.97	11.18	20.804	20.968
8	125	50	15	9.75	9.96	19.780	19.965
9	125	55	25	8.96	9.17	19.046	19.247

5. Results and Discussion

From the observation table, it is clears that the diffused wire gives more material removal rate as compared to brass wire. The response tables of S/N ratio for MRR using brass wire and diffused wire are shown in table 4.2 and table 4.3 respectively.

The delta values and ranks for pulse on time, pulse off time and servo voltage are 4.66, 2.56, 1.63 and 1, 2 and 3 respectively, as shown in response table 4.2 for S/N ratio (MRR) using brass wire. Similarly from table 4.3 i.e. the response table for S/N ratio (MRR) using diffused wire, the delta values and ranks for input parameters viz. pulse on time, pulse off time and servo voltage are 4.53, 2.48 and 1.58 and 1, 2 and 3 respectively. From these tables it is evident that the parameter having highest delta value gets highest rank. The pulse on time gets rank 1 followed by pulse off time and servo voltage. The rank shows the relative importance of each input factor to the response. The ranks and delta values indicates that the pulse on time (Ton) has the highest impact on the material removal rate (MRR) followed by the pulse off time and servo voltage.

Table 5 Response Table for S/N Ratio using Brass Wire

Level	Ton	Toff	SV
1	15.22	19.33	18.62
2	18.44	17.45	17.92
3	19.88	16.76	17.00
Delta	4.66	2.56	1.63
Rank	1	2	3

Table 6 Response Table for S/N Ratio Using Diffused Wire

Level	Ton	Toff	SV
1	15.53	19.51	18.84
2	18.64	17.70	18.14
3	20.06	17.03	17.26
Delta	4.53	2.48	1.58
Rank	1	2	3

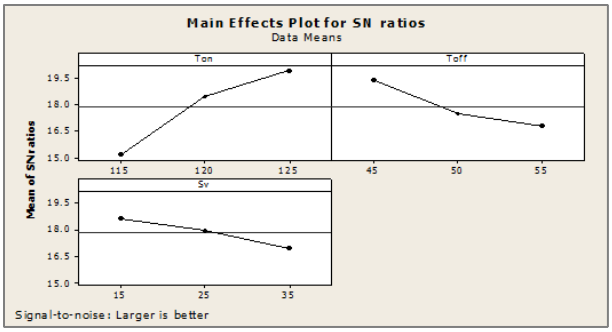

Fig. 2 Main Effects plot for S/N Ratio using Brass Wire

During the process of Wire-Cut EDM, the effect of various input parameter like pulse on time, pulse off time and servo voltage has significant effect on MRR as shown in main effect plot for S/N ratio of MRR. These graphs clearly show that as the pulse on time increases, the material removal rate also increases. On the other hand, as the pulse off time increases, the material removal rate decreases.

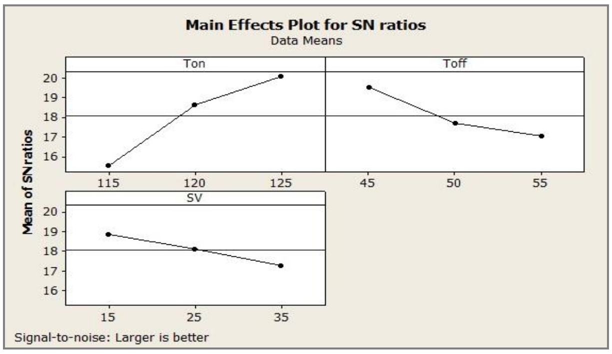

Fig. 3 Main Effects plot for S/N Ratio using Diffused Wire

This is because the discharge energy increases with the increase in pulse on time and peak current leading to a higher material removal rate. And as the pulse off time decreases, the number of discharges within a given period becomes more which leads to a higher material removal rate. With increase in spark gap set voltage the average discharge gap gets widened resulting into a lower material removal rate.

Table 7 Analysis of Variance for S/N Ratio using Brass Wire

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
Ton	2	34.1690	34.1690	17.0845	33.06	0.029	68.65
Toff	2	10.5728	10.5728	5.2864	10.23	0.089	21.24
Sv	2	3.9911	3.9911	1.9956	3.86	0.206	8.01
Error	2	1.0335	1.0335	0.5167			
Total	8	49.7664					

Table 8 Analysis of Variance for S/N Ratio using Diffused Wire

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
Ton	2	32.1611	32.1611	16.0805	31.39	0.031	68.75
Toff	2	9.8483	19.8483	4.9242	9.61	0.094	21.05
Sv	2	3.7416	3.7416	1.8708	3.45	0.215	7.99
Error	2	1.0245	1.0245	0.5123			
Total	8	46.7755					

In an analysis of variance table, the P value indicates the most significant parameter. The factor whose P value is less than 0.05 will be most effective parameter. The analysis of variance tables for S/N ratio for both the wires shows that the servo voltage is not important for influencing MRR and the value of pulse on time and pulse off time is most affected the MRR. From these tables it is clearly definite that pulse on time is the most effective parameter for material removal rate followed by pulse off time and last one is the servo voltage.

Conclusions

It is observed that diffused wire gives more material removal rate (MRR) as compared to the brass wire. After analyzing S/N graphs and mean plots for optimal conditions for Material Removal Rate, it is observed that the MRR increases with the increase in pulse on time, and decreases with increase in pulse off time and servo voltage. This is because the discharge energy increases with the pulse on time and peak current leading to a faster cutting rate. As the pulse off time decreases, the number of discharges within a given period becomes more which leads to a higher cutting rate. With increase in servo voltage the average discharge gap gets widened resulting into a lower cutting rate.

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